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Composition ship collision risk based on fuzzy theory

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Abstract: Despite of modern navigation devices, there are problems in navigation of vessels in waterways due to the geographical structures, disturbances in water, dynamic nature, and heavily environmental influenced sea traffic. Even though all vessels are equipped with modern navigation devices, the accidents are reported caused by various reasons and mainly by human factor according to investigation. We propose an effective and efficient composition collision risk calculation method for finding the collision probability and avoiding the collision between ships in possible collision situations. The proposed composition collision risk calculation method at ship's position using combination of fuzzy and fuzzy comprehensive evaluation methods. The algorithm is straightforward to implement and is shown to be effective in automatic ship handling for ships involved in complex navigation situations. Experiments are carried out with indigenous data and the results show the effectiveness of the proposed approach.

Key words: automatic ship navigation; collision risk; fuzzy theory

1 Introduction

Recently, precision of positioning using GPS becomes considerably better and discussion about mandatory installation of automatic identification system (AIS) for ships is in progress on the international maritime organization (IMO). Using these devices, each ship will be able to obtain its own position exactly and also easily derive information about other ship's position, heading, speed and so on [1].

Collision avoidance starts from assessing collision risk, and there are several ways to define it. The concept of a ship domain proposed by Fujii may be used to assess collision risk. This concept is succeeded by GOODWIN [2] in several shapes, but it does not contain time-related information.

Ship collision risk calculation is one of the most important parts in the ship navigation system [3−4]. The first one is traffic flow theory which uses ship collision rate and collision probability to evaluate the collision risk for special water area. The second is ship domain and arena which is based on human praxeology and psychology. In Refs. [5−6], the authors use different approaches to calculate collision risk. In the third stage, people have considered the distance of closest point approach (DCPA) and the time of closest point approach (TCPA) in calculation, as discussed in Ref. [4]. In the fourth stage, DCPA and TCPA are combined, and weighting method is adopted to calculate collision risk at the beginning [7−8]. This method exists obvious disadvantage that DCPA and TCPA are two different variables. Then, people adopt fuzzy theory to combine DCPA and TCPA. At present, most researches are based on the artificial intelligent technology as fuzzy theory, expert system and neural network to calculate the collision risk [9−13].

In this work, we present the composition collision risk calculation which calculates the collision risk between ships at current time based on combination of fuzzy and fuzzy comprehensive evaluation method. In this module, firstly, we present a mechanism to calculate the DCPA and TCPA of each ship using the state information of ships that are received from radar. Secondly, the collision risk (C_1) will be calculated based on fuzzy theory after inputting the DCPA and TCPA. Meanwhile, the C_2 is calculated based on the membership functions of DCPA and TCPA, distance between ships (d) and navigation angle of target ship. Thirdly, the C_1 and C_2 are used in fuzzy system again to get the composition collision risk at time t_x.

2 Composition risk based collision avoidance

2.1 DCPA and TCPA calculation

In this section, we introduce the collision risk calculation module that will calculate the collision risk at

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current time. Figure 1 shows the flowchart of collision risk calculation at current time. Firstly, we find the state information of each ship by the VTS radar scanning at current time. Then, the DCPA and TCPA are calculated based on ship's position and navigation angle. After that, the DCPA and TCPA are input to fuzzy logic system and the C_1 and C_2 are calculated based on membership functions of navigation angle, distance between two ships, DCPA and TCPA. At last, the composition collision risk of current time will be calculated using fuzzy theory again.

Figure 2 displays the two vessels, labeled as ship *O* (own ship) and ship *T* (target ship). Both vessels move with different speeds and courses. The bold red arrow indicates DCPA between ship *O* and ship *T*, to precisely measure the degree of collision risk among the vessels.

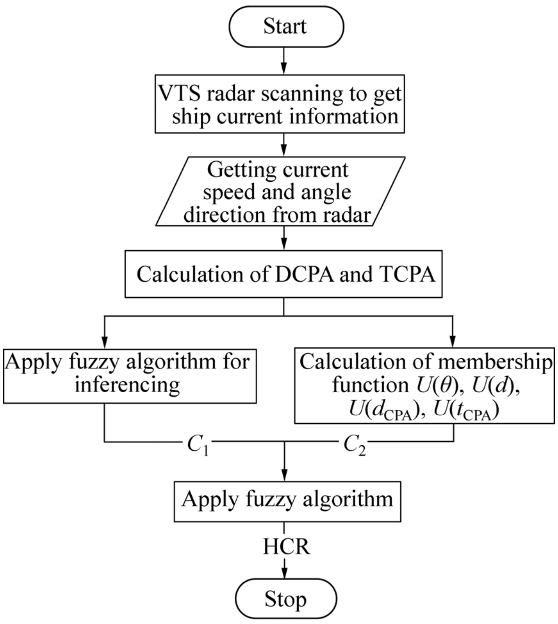

Fig. 1 Composition collision risk calculation module of proposed system

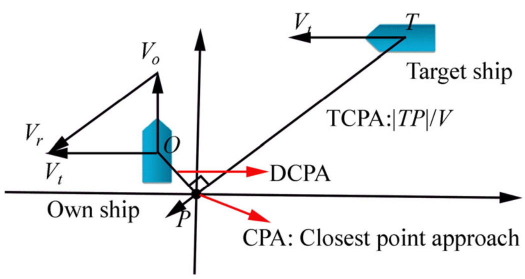

Fig. 2 DCPA and TCPA calculation

Figure 3 demonstrates the whole scenario. The vessel maneuvers towards northeast while the vessel maneuvers towards northwest. Both the vessels move with different speeds and courses. To find the DCPA and TCPA between vessel *O* and *T*, we calculate the relative speed of own ship to the target ship using Eq. (1). The relative speed is depicted in Fig. 3. Figure 3 shows that a

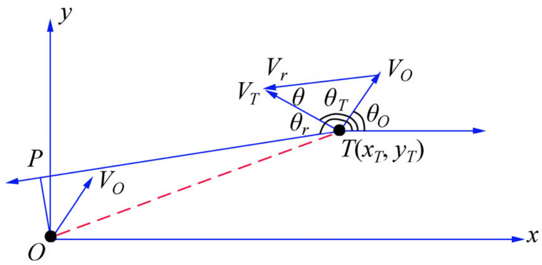

Fig. 3 Scenario for DCPA and TCPA calculation

perpendicular line is drawn on the own ship from the parallel direction of the target ship. The distance between the parallel direction of target ship's position and the own ship's position is DCPA, as calculated by Eq. (5).

The relative speed to target ship measured from own ship is calculated as

$$V_r=\sqrt{V_O^2+V_T^2-2\,|V_O\cdot V_T|\cos(\theta_T-\theta_O)} \tag{1}$$

We define the slope intercept of line *TP* which is parallel with relative speed and starts from target ship's position:

$$k=\tan\theta_r \tag{2}$$

$$\theta_r=\theta_T+\theta \tag{3}$$

$$\theta=\arccos\left(\frac{V_r^2+V_T^2-V_O^2}{2V_r\cdot V_T}\right) \tag{4}$$

where *k* is the slope of the line *TP*, which is relative to the angle between relative velocity and target velocity of current time.

Mathematically, at current time, the DCPA between vessels *O* and *T* from VTS can be calculated by using the following equations:

$$d_{\mathrm{CPA}}=|OP|=\frac{|y_T-x_T\tan\theta_r|}{\sqrt{\tan^2\theta_r+1}} \tag{5}$$

Mathematically, at current time, the TCPA between vessels *O* and *T* from VTS can be calculated by using the following equations:

$$|TP|=\sqrt{|OT|^2-|OP|^2}=\sqrt{(x_T^2+y_T^2)-d^2} \tag{6}$$

where *OT* is the distance between own ship and target ship, and *OP* is the perpendicular line from own ship to line *TP* at current time.

$$t_{\mathrm{CPA}}=\frac{|TP|}{V_r}=\frac{\sqrt{(x_T^2+y_T^2)-d_{\mathrm{CPA}}^2}}{V_r} \tag{7}$$

2.2 Fuzzy rules based collision risk calculation

In this section, we elaborate our approach of using fuzzy system for collision risk calculation.

Table 1 gives the five linguistic values for the variables TCPA, DCPA, and C_1.

Table 1 Rules for DCPA, TCPA and C_1 membership functions

DCPA/m	Value	TCPA/s	Value	C_1	Value
0−2	S	0−4	S	0−0.4	L
1−3	MS	2−6	MS	0.2−0.6	ML
2−4	M	4−8	M	0.4−0.8	M
3−5	MB	6−10	MB	0.6−1.0	MH
4−6	B	8−10	B	0.8−1.0	H

Table 2 gives the reasoning rules of degree of C_1. For example, when DCPA is S and TCPA is S, the C_1 will be considered as H.

Table 2 Reasoning rule of degree of C_1

TCPA	DCPA				
	S	MS	M	MB	B
S	H	H	MH	MH	MH
MS	H	MH	M	M	M
M	MH	M	M	ML	ML
MB	MH	M	ML	ML	L
B	MH	M	ML	L	L

In our case, the reasoning can be expressed in linguistic rules of two-input and one-output system. DCPA and TCPA are the process state variables, and C_1 is the control variable. Here, we generate 25 rules for C_1 of our proposed system.

2.3 Fuzzy comprehensive evaluation based collision risk calculation

This section explains the procedure of C_2 calculation based on fuzzy comprehensive evaluation. The comprehensive evaluation result can be used as both subjective and objective evaluation. We can get perfect result through assessing the reduction of the affecting factors. So, we don't use the weighting of DCPA and TCPA to calculate collision risk, but apply fuzzy comprehensive evaluation to calculate C_2. There are many factors affecting C_2. We only consider the major factors here: the distance between target ship and local ship at current time, the position of target ship, DCPA and TCPA at current time.

So, the target factors' discourse domain is

$$u=\{d, \theta, t_{\mathrm{CPA}}, d_{\mathrm{CPA}}\} \tag{8}$$

The allocation of target factors weight is

$$\begin{cases} A = w_d, w_\theta, w_{d_{\mathrm{CPA}}}, w_{t_{\mathrm{CPA}}} \\ w_d > 0,\ w_\theta > 0,\ w_{d_{CPA}} > 0,\ w_{t_{CPA}} > 0 \\ w_d + w_\theta + w_{d_{\mathrm{CPA}}} + w_{t_{\mathrm{CPA}}} = 1 \end{cases} \tag{9}$$

w_d=0.12, w_θ=0.12, $w_{d_{\mathrm{CPA}}} = 0.38$, $w_{t_{\mathrm{CPA}}} = 0.38$.

Target evaluation matrix is

$$\boldsymbol{B} = \begin{bmatrix} r_d \\ r_\theta \\ r_{d_{\mathrm{CPA}}} \\ r_{t_{\mathrm{CPA}}} \end{bmatrix} \tag{10}$$

where r_d, r_θ, $r_{d_{\mathrm{CPA}}}$ and $r_{t_{\mathrm{CPA}}}$ are target risk memberships.

The risk membership function of distance between two ships at current time is

$$u(d) = \begin{cases} 1,\ d \le d_1 \\ [(d_\mathrm{m} - d)/(d_\mathrm{m} - d_1)]^2,\ d_1 < d \le d_\mathrm{m} \\ 0,\ d > d_\mathrm{m} \end{cases} \tag{11}$$

$$R = 1.7\cos(\theta - 19^\circ) + \sqrt{4.4 + 2.89\cos^2(\theta - 19^\circ)}$$
$$(0^\circ \le \theta < 360^\circ)$$

$$d_\mathrm{m} = K_1 \cdot K_2 \cdot K_3 \cdot R$$

$$d_1 = K_1 \cdot K_2 \cdot K_3 \cdot D_\mathrm{L}$$

where d_1 is distance of the last minute avoidance and is the distance of the adopt avoidance action at current time; K_1 is decided by visibility, K_2 by water area status, and K_3 by human factor; D_L is the distance of the last minute action; R is the radius of arena at current time.

Position of target ship membership function at current time is

$$u(\theta) = \begin{cases} \dfrac{1}{1 + (\theta/\theta_0)^2},\ 0 \le \theta < 180^\circ \\ \dfrac{1}{(\dfrac{360^\circ - \theta}{\theta_0})^2},\ 180^\circ \le \theta < 360^\circ \end{cases} \tag{12}$$

where θ is according to the velocity ratio K of local ship and target ship.

$$K = \frac{v_0}{v_t} \tag{13}$$

$$\theta_0 = \begin{cases} 40^\circ,\ K < 1 \\ 90^\circ,\ K < 1 \\ 180^\circ,\ K > 1 \end{cases}$$

DCPA risk membership function at current time is

$$u(d_{\mathrm{CPA}}) = \begin{cases} 1,\ d_{\mathrm{CPA}} \le \lambda \\ \dfrac{1}{2} - \dfrac{1}{2}\sin[\dfrac{\pi}{d_{\mathrm{CPA}_0} - \lambda}(d_{\mathrm{CPA}} - \dfrac{d_{\mathrm{CPA}_0} + \lambda}{2})], \\ \qquad \lambda < d_{\mathrm{CPA}} \le d_{\mathrm{CPA}_0} \\ 0,\ d_{\mathrm{CPA}} > d_{\mathrm{CPA}_0} \end{cases} \tag{14}$$

d_{CPA_0}=1 n mile, λ=2(L_o+L_t), and L_o and L_t are the lengths of local and target ship, respectively.

TCPA risk membership function at current time is

$$u(t_{\mathrm{CPA}})=\begin{cases}1, \ t_{\mathrm{CPA}} \le t_1 \\ \dfrac{t_2-t_{\mathrm{CPA}}}{t_2-t_1}, \ t_1 < t_{\mathrm{CPA}} \le t_2 \\ 0, \ t_{\mathrm{CPA}} > t_2\end{cases} \tag{15}$$

$$t_1=\frac{\sqrt{(d_1^2-\lambda^2)}}{v_{\mathrm{s}}} \tag{16}$$

$$t_2=\frac{\sqrt{(d_{\mathrm{m}}^2-d_{\mathrm{CPA}_0}^2)}}{v_{\mathrm{s}}} \tag{17}$$

According to the fuzzy comprehensive evaluation method, there is

$$C_2=\boldsymbol{A}\cdot\boldsymbol{B}=[w_d \ \ w_\theta \ \ w_{d_{\mathrm{CPA}}} \ \ w_{t_{\mathrm{CPA}}}]\cdot\begin{bmatrix}r_d \\ r_\theta \\ r_{d_{\mathrm{CPA}}} \\ r_{t_{\mathrm{CPA}}}\end{bmatrix} \tag{18}$$

C_2 at current time is

$$C_2=w_d u_d+w_\theta u_\theta+w_{d_{\mathrm{CPA}}}u_{d_{\mathrm{CPA}}}+w_{t_{\mathrm{CPA}}}u_{t_{\mathrm{CPA}}} \tag{19}$$

2.4 Composition collision risk calculation method

In this section, based on these computations, we introduce our composition collision risk calculation technique. The technique utilizes both C_1 and C_2 in order to obtain the better results. The algorithm is based on steps depicted in Fig. 1.

Once we compute the values for C_1 and C_2, we need to know which collision risk is better in order to obtain a fuzzy function to compute the HCR by combining C_1 and C_2. Table 3 depicts the rules for the fuzzy function.

Table 3 Rules for membership functions

C_1	Value	C_2	Value	HCR	Value
0−0.4	L	0−0.4	L	0−0.4	L
0.2−0.6	ML	0.2−0.6	ML	0.2−0.6	ML
0.4−0.8	M	0.4−0.8	M	0.4−0.8	M
0.6−1.0	MH	0.6−1.0	MH	0.6−1.0	MH
0.8−1.0	H	0.8−1.0	H	0.8−1.0	H

Now, we design five linguistic values for the variables HCR, as shown in Table 3. We input the C_1 and C_2 to the fuzzy system and HCR is produced as a composite collision risk.

Table 4 shows the reasoning rules of degree of HCR. The fuzzy reasoning rule tables, in case when CR1 is L, ML, M, MH and H can be expressed in the forms of table.

In this case, the reasoning can be expressed in linguistic rules of two-input one-output system. C_1 and C_2 are the process state variables, and HCR is the control variable.

Table 4 Reasoning rule of degree of composition collision risk

C_2	C_1				
	L	ML	M	MH	H
L	L	L	ML	M	MH
ML	L	ML	ML	M	MH
M	ML	ML	M	M	MH
MH	M	M	M	HL	H
H	MH	MH	HH	H	H

In the case of composition collision risk calculation at current time, we design the membership functions for C_1, C_2 and composition collision risk at current time in our proposed system. Figures 4 and 5 display the fuzzy membership functions graphically of C_1 and C_2, respectively. Figure 6 displays the fuzzy membership function of degree of composition collision risk graphically.

Figure 4 shows the membership function of C_1. C_1 is defined by five linguistic variables using membership functions, which are defined between 0 and 1.

Figure 5 shows the membership function of C_2. C_2 is also defined by five linguistic variables using membership functions, which are defined between 0

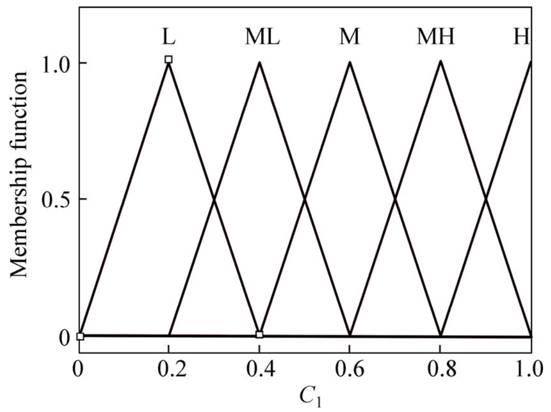

Fig. 4 Membership function of C_1

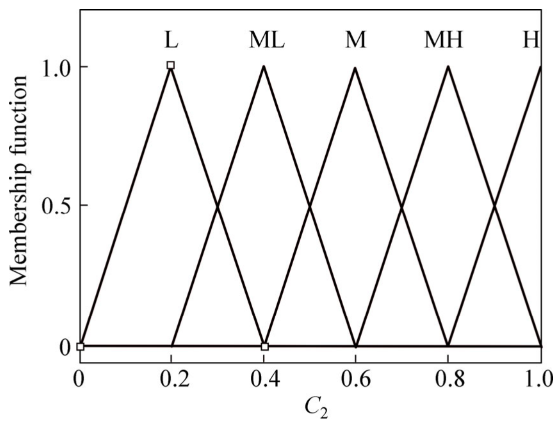

Fig. 5 Membership function of C_2

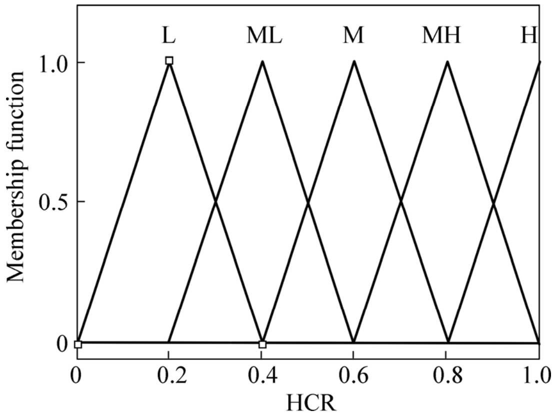

Fig. 6 Membership function degree of composition collision risk

and 1.

Figure 6 shows the membership function of degree of HCR. The reasoning fuzzy table to determine HCR is provided using C_1 and C_2. HCR is defined between 0 and 1.

3 Simulation and performance analysis

3.1 Simulation environment

To validate the proposed system, we developed a real-time simulator which can get the real time status information of ships. We programmed the simulator by using C# and the experimental environment is given in Table 5.

3.2 Implementation results of simulator

In the real navigation situation, there are mainly three situations: head-on, overtaking and crossing. However, we carried out experiments with two situations i.e. head-on and overtaking, to test the performance of the system. We evaluate the performance of the proposed composition collision risk method with fuzzy collision risk and evaluation collision risk for two different scenarios depicted in Figs. 7 and 8.

Figure 9 shows the display of simulator. The display of simulator is divided into map screen, initial information of ships input center, ship control center, prediction of ships visual window, collision risk visual window, real-time information window and best deflection control window.

3.3 Simulation results and performance analysis

Figures 10 and 11 show performance comparison between proposed composition collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation for two scenarios presented in Figs. 7 and 8, respectively. We record the results of each scenario by using our proposed system and displaying

Table 5 Simulation environment

Module	Hardware	Software	Remark
Vessel information collection module	Intel(R) Xeon(R) CPUW3503 @2.4 GHz 2.39 GHz 4 GB RAM	Microsoft Visual Studio	C# Windows 7
DCPA and TCPA calculation module	Intel(R) Xeon(R) CPUW3503 @2.4 GHz 2.39 GHz 4 GB RAM	Microsoft Visual Studio	C# Windows 7
Collision risk calculation module	Intel(R) Xeon(R) CPUW3503 @2.4 GHz 2.39 GHz 4 GB RAM	Microsoft Visual Studio	C# Windows 7
Vessel location prediction module	Intel(R) Xeon(R) CPUW3503 @2.4 GHz 2.39 GHz 4 GB RAM	MatlabR2010a and Microsoft Visual Studio	Windows 7
Avoidance control module	Intel(R) Xeon(R) CPUW3503 @2.4 GHz 2.39 GHz 4 GB RAM	Microsoft Visual Studio	C# Windows 7

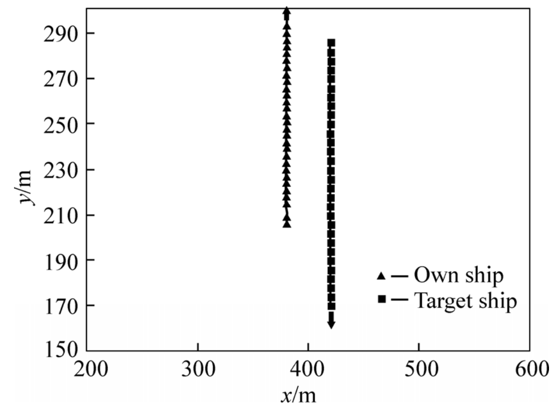

Fig. 7 Navigation of head-on scenario

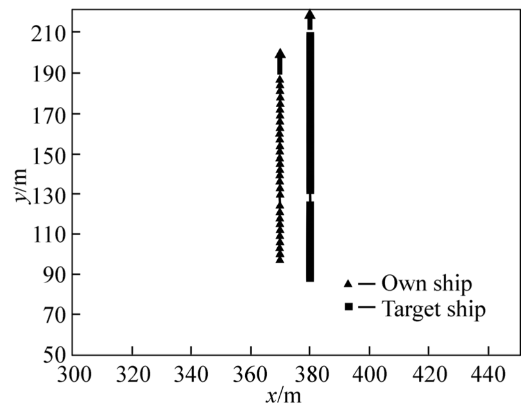

Fig. 8 Navigation of overtaken scenario

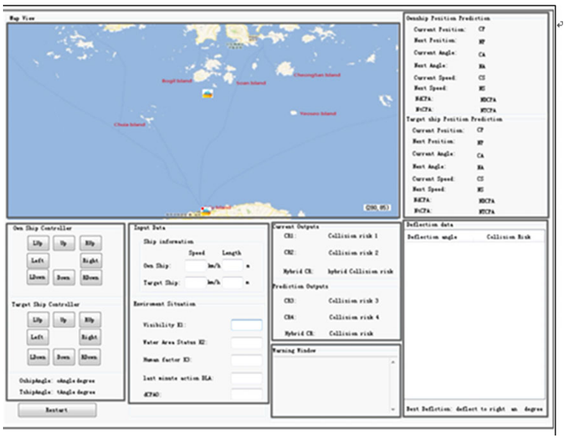

Fig. 9 Display of simulator

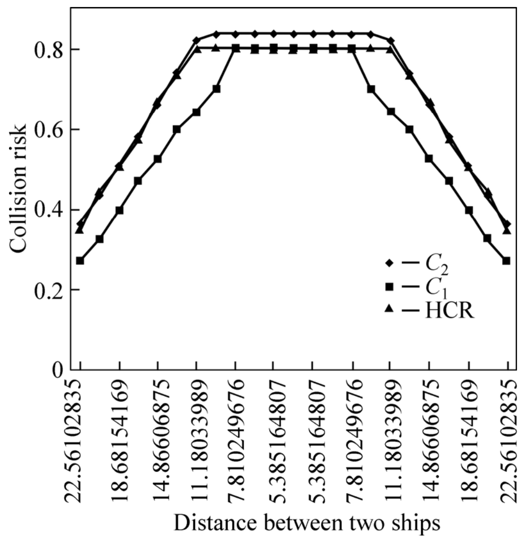

Fig. 10 Simulation result of head-on scenario

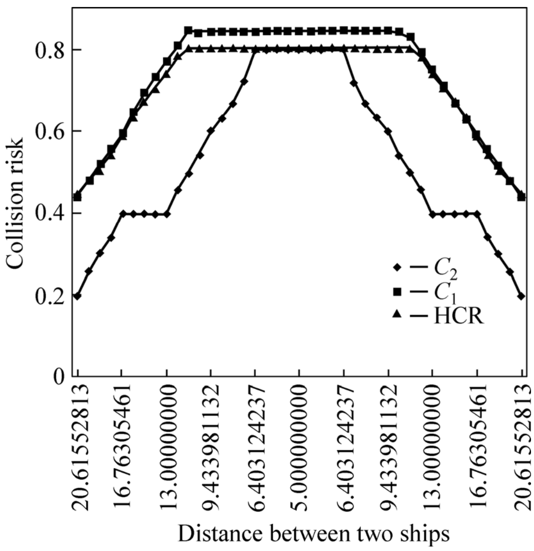

Fig. 11 Simulation results of overtaken scenario

the comparative results. To the best of our knowledge, the existing schemes just calculated the collision risk by using two ships. However, we carried out the simulation in a congested area and calculated the collision risk with all the ships at a certain distance from the own ship. We also calculated the composition collision risk for better comparison.

In the head-on scenario, we set that own vessel and target vessel move with the same speed of 3 m/s, as shown in Fig. 8. We set 90° for own vessel and 270° for target vessel while the starting points of both ships are different. We performed the simulation and recorded the results.

Figure 10 shows the variation of composition collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation. In this scenario, two ships pass nearby each other with a certain distance. When the ships start moving towards each other, this distance is long and the DCPA and TCPA are also high, which means that the collision risk is low. As the two ships approach each other, the distance between two ships decreases, and the collision risk is linearly increased. When the two ships reach each other and the distance between them is constant (remains the same) for a certain time, the collision risk is uniform for that period. However, when the two ships cross each other and the distance between them increases, the collision risk is linearly decreased. The results show that composition collision risk performance is better than other techniques. This is because that of composition collision risk computes risk value more efficiently than individual risk computation. Furthermore, composition collision risk computes risk by using next predicted position. Our experiments show that comparison of C_1 and C_2 has significant impact on the output of the risk computation.

In the overtaken scenario, we examined our composition algorithm when two ships have different speeds. Figure 9 shows the route of own ship and target ship scenario. We set that own ship and target ships move with the speed of 3 m/s and 4 m/s, respectively. And we changed the courses of own and target ships from previous degree to 90° and performed the simulation. The simulation results can be seen in Fig. 11.

Figure 11 shows the variation of composition collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation. We can see when the target ship overtakes own ship from long distance to approach each other, the collision risk is increased linearly, and when the target ship approaches own ship, the collision risk is uniform for a certain period of time. However, when the own ship is overtaken by target ship, the collision risk is decreased linearly. The results show that composition collision risk performance is better than that of other techniques.

4 Conclusions

This work has presented a method for automatic composition collision risk calculation and collision avoidance to control ship to be used in an automatic navigation system.

We describe the approach of composition collision risk calculation which combines the theories of fuzzy logic, fuzzy comprehensive evaluation and the conventional risk calculation techniques in order to enhance the accuracy of existing research. Besides, we also propose the method that gives the best action in advance to prevent the collision accident when there is a collision possibility. The proposed approach is illustrated with two navigation situations, i.e. head-on and overtaking. Experiments have been performed in order to test quality of the proposed system.

Acknowledgments

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